

# New Predictions for Neutrino Telescope Event Rates

Raj Gandhi<sup>a</sup>, Chris Quigg<sup>b</sup>, M. H. Reno<sup>c</sup>, and Ina Sarcevic<sup>d\*</sup>

<sup>a</sup>Mehta Research Institute, 10, Kasturba Gandhi Marg, Allahabad 211002, India

<sup>b</sup>Fermi National Accelerator Laboratory, Batavia, IL 60510 USA

<sup>c</sup>Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242 USA

<sup>d</sup>Department of Physics, University of Arizona, Tucson, AZ 85721 USA

Recent measurements of the small- $x$  deep-inelastic regime at HERA translate to new expectations for the neutrino-nucleon cross section at ultrahigh energies. We present event rates for large underground neutrino telescopes based on the new cross section for a variety of models of neutrino production in Active Galactic Nuclei, and we compare these rates with earlier cross section calculations.

Neutrino telescopes such as AMANDA, BAIKAL, DUMAND II and NESTOR [1] have the potential to extend the particle physics frontier beyond the standard model, as well as probe stars and galaxies. At ultrahigh energies ( $E_\nu > 1$  TeV), neutrinos are decay products of pions produced in cosmic ray interactions. Undeflected by magnetic fields and with long interaction lengths, neutrinos can reveal information about astrophysical sources. Gamma-rays, on the other hand, get absorbed by a few hundred gm of material. Active Galactic Nuclei (AGNs) [2] may be prodigious sources of high energy neutrinos as well as gamma-rays. Neutrino telescopes span a significant fraction of the sky at all times, making the observation of neutrino interactions in or near the detector feasible. If the most optimistic flux predictions are accurate, observations of AGNs via neutrino telescopes may be imminent.

Here we present predictions of event rates for several models of the AGN neutrino flux [3–5]. We also compare the predicted rates with the atmospheric neutrino background (ATM), *i.e.*, neutrinos produced by cosmic ray interactions in the atmosphere [6]. These rates reflect a new calculation of the neutrino-nucleon cross section which follows from recent results from the HERA  $ep$  collider [7]. To reduce the background from muons

produced in the atmosphere, it is sufficient to consider the upward-going muons produced below the detector via  $\nu_\mu$  ( $\bar{\nu}_\mu$ )-N interactions. We also give predictions for downward-moving (contained) muon event rates due to  $\bar{\nu}_e e$  interactions in the PeV range.

The importance of the HERA experimental results for neutrino-nucleon cross sections is in measurements of structure functions at small parton momentum fractions  $x$  and large momentum transfers  $Q$ . At ultrahigh energies, the  $\nu N$  cross section is dominated by  $Q \sim M_W$ , the mass of the  $W$ -boson. Consequently,  $x \sim M_W^2/(2ME_\nu\langle y \rangle)$ , in terms of nucleon mass  $M$ , and  $x$  decreases as the incident neutrino energy  $E_\nu$  increases. HERA results cover the interval  $10^{-4} \lesssim x \lesssim 10^{-2}$  and  $8.5 \text{ GeV}^2 \lesssim Q^2 \lesssim 15 \text{ GeV}^2$  [7], and guide theoretical small- $x$  extrapolations of the parton distributions at even smaller values of  $x$ . Compared to pre-HERA cross section calculations [8], the new cross section calculation is approximately a factor of four to ten times larger at the highest energies ( $E_\nu = 10^9$  TeV) [9]. The range of values reflects different parton distribution function parameterizations and extrapolations below  $x = 10^{-5}$ , all consistent with the data at higher  $x$ . Since the larger cross section also implies greater attenuation of neutrinos in the Earth, upward-muon event rates for neutrino energy thresholds in the 1-10 TeV range are only 15% larger than

---

\*Talk presented by I. Sarcevic.

previous results based on old cross sections [8].

The attenuation of neutrinos in the Earth is described by a shadow factor  $S(E_\nu)$ , equivalent to the effective solid angle for upward muons, normalized to  $2\pi$ :

$$\frac{dS(E_\nu)}{d\Omega} = \frac{1}{2\pi} \exp\left(-z(\theta)N_A\sigma_{\nu N}(E_\nu)\right), \quad (1)$$

where  $N_A = 6.022 \times 10^{23} \text{ mol}^{-1} = 6.022 \times 10^{23} \text{ cm}^{-3}$  (water equivalent) is Avogadro's number, and  $z(\theta)$  is the column depth of the earth, in water equivalent units, which depends on zenith angle [10]. The probability that the neutrino converts to a muon that arrives at the detector with  $E_\mu$  larger than the threshold energy  $E_\mu^{\min}$  is proportional to the cross section:

$$P_\mu(E_\nu, E_\mu^{\min}) = \sigma_{CC}(E_\nu)N_A\langle R(E_\nu, E_\mu^{\min}) \rangle, \quad (2)$$

where the average muon range in rock is  $\langle R \rangle$  [11]. A more detailed discussion appears in Ref. [9].

The diffuse flux of AGN neutrinos, summed over all AGN sources, is isotropic, so the event rate is

$$\text{Rate} = A \int dE_\nu P_\mu(E_\nu, E_\mu^{\min}) S(E_\nu) \frac{dN_\nu}{dE_\nu}, \quad (3)$$

given a neutrino spectrum  $dN_\nu/dE_\nu$  and detector cross sectional area  $A$ . As the cross section increases,  $P_\mu$  increases, but the effective solid angle decreases.

In Tables 1 and 2, we show the event rates for a detector with  $A = 0.1 \text{ km}^2$  for  $E_\mu^{\min} = 1 \text{ TeV}$  and  $E_\mu^{\min} = 10 \text{ TeV}$ , respectively. These event rates are for upward muons and antimuons with two choices of parton distribution functions: EHLQ parton distribution functions [12] used in Ref. [8], and the parton distributions parameterized by the CTEQ Collaboration [13], coming from a global fit that includes the HERA data. The muon range is that of Ref. [11].

The representative fluxes in Tables 1 and 2 can be approximated by a simple power law behavior for  $E_\nu < 100 \text{ TeV}$ . For  $dN/dE_\nu \propto E^{-\gamma}$ , the fluxes can be approximated by  $\gamma = 0$  (AGN-SS),  $\gamma = 2$  (AGN-NMB and AGN-SP) and  $\gamma = 3.6$  (ATM). The AGN-SP rate is large compared to the AGN-NMB rate because additional mechanisms are included. Flux limits from the Fréjus

Table 1

Number of upward  $\mu + \bar{\mu}$  per year per steradian for  $A = 0.1 \text{ km}^2$  and  $E_\mu^{\min} = 1 \text{ TeV}$ .

Fluxes	EHLQ	CTEQ-DIS
AGN-SS [3]	82	92
AGN-NMB [4]	100	111
AGN-SP [5]	2660	2960
ATM [6]	126	141

Table 2

As in Table 1, but for  $E_\mu^{\min} = 10 \text{ TeV}$ .

Fluxes	EHLQ	CTEQ-DIS
AGN-SS [3]	46	51
AGN-NMB [4]	31	34
AGN-SP [5]	760	843
ATM [6]	3	3

experiment are inconsistent with the SP flux for  $1 \text{ TeV} < E_\nu < 10 \text{ TeV}$  [14].

The flatter neutrino spectra have larger contributions to the event rate for muon energies away from the threshold muon energy than the steep atmospheric flux. For the 10 TeV muon energy threshold, the atmospheric neutrino background is significantly reduced.

Finally we consider event rates from electron neutrino and antineutrino interactions. For  $\nu_e N$  (and  $\bar{\nu}_e N$ ) interactions, the cross sections are identical to the muon neutrino (antineutrino) nucleon cross sections. Because of the rapid energy loss or annihilation of electrons and positrons, it is generally true that only contained events can be observed. Since electron neutrino fluxes are small, unrealistically large effective volume is needed to get measurable event rates. The exception is at  $E_\nu = 6.3 \text{ PeV}$ , precisely the energy for resonant  $W$ -boson production in  $\bar{\nu}_e e$  collisions. The contained event rate for resonant  $W$  production is

$$\text{Rate} = \frac{10}{18} V_{\text{eff}} N_A \int dE_{\bar{\nu}} \sigma_{\nu e}(E_\nu) S(E_{\bar{\nu}}) \frac{dN}{dE_{\bar{\nu}}}. \quad (4)$$

Table 3

Downward resonance  $\bar{\nu}_e e \rightarrow W^-$  events per year per steradian for a detector with effective volume  $V_{\text{eff}} = 1 \text{ km}^3$  together with the potential downward (upward) background from  $\nu_\mu$  and  $\bar{\nu}_\mu$  interactions above 3 PeV.

Mode	AGN-SS [3]	AGN-SP [5]
$W \rightarrow \bar{\nu}_\mu \mu$	6	3
$W \rightarrow \text{hadrons}$	41	19
$(\nu_\mu, \bar{\nu}_\mu) \text{ N CC}$	33 (7)	19 (4)
$(\nu_\mu, \bar{\nu}_\mu) \text{ N NC}$	13 (3)	7 (1)

We show event rates for resonant  $W$ -boson production in Table 3.

From Table 3 we note that a  $1 \text{ km}^3$  detector with energy threshold in PeV range would be suitable for detecting resonant  $\bar{\nu}_e \rightarrow W$  events, however, the  $\nu_\mu N$  background may be difficult to overcome. By placing the detector a few km underground, one can reduce atmospheric-muon background, which is 5 events per year per steradian at the surface of the Earth.

In summary, we find that detectors such as DUMAND II, AMANDA, BAIKAL and NESTOR have a very good chance of being able to test different models for neutrino production in the AGNs [2]. For  $E_\mu^{\text{min}} = 1 \text{ TeV}$ , we find that the range of theoretical fluxes lead to event rates of 900-29,600 upward-moving muons/yr/km<sup>2</sup>/sr originating from the diffuse AGN neutrinos, with the atmospheric background of 1400 events/yr/km<sup>2</sup>/sr. For  $E_\mu^{\text{min}} = 10 \text{ TeV}$ , signal to background ratio becomes even better, with signals being on the order of 500-8,400 events/yr/km<sup>2</sup>/sr, a factor  $\sim 20$ -300 higher than the background rate. For neutrino energies above 3 PeV there is significant contribution to the muon rate due to the  $\bar{\nu}_e$  interaction with electrons, due to the  $W$ -resonance contribution. We find that acoustic detectors with 3 PeV threshold and with effective volume of  $0.2 \text{ km}^3$ , such as DUMAND, would detect 48 hadronic cascades per year from  $W \rightarrow \text{hadrons}$ , 7 events from  $W \rightarrow \mu \bar{\nu}_\mu$  and 36 events from  $\nu_\mu$  and  $\bar{\nu}_\mu$  interactions with virtually no background from ATM neutrinos.

## REFERENCES

1. J. Babson *et al.*, (DUMAND Collaboration), Phys. Rev. D42 (1990) 3613; Proceedings of the NESTOR workshop at Pylos, Greece, ed. L. K. Resvanis (University of Athens, 1993); D. Lowder *et al.*, Nature 353 (1991) 331.
2. See §7 of T. K. Gaisser, F. Halzen and T. Stanev, Phys. Rep. 258 (1995) 173 for a review of several models.
3. F. W. Stecker, C. Done, M. H. Salamon and P. Sommers, Phys. Rev. Lett. 66 (1991) 2697; Errat.: Phys. Rev. Lett. 69 (1992) 2738. Revised estimates of the neutrino flux appear in F. W. Stecker and M. H. Salamon, astro-ph/9501064, submitted to Space Sci. Rev.
4. L. Nellen, K. Mannheim and P. L. Biermann, Phys. Rev. D47 (1993) 5270.
5. A. P. Szabo and R. J. Protheroe, Astropart. Phys. 2 (1994) 375.
6. L. V. Volkova, Yad. Fiz. 31 (1980) 1510 (Sov. J. Nucl. Phys. 31 (1980) 784).
7. ZEUS Collaboration, M. Derrick *et al.*, Phys. Lett. B316 (1993) 412; H1 Collaboration, I. Abt *et al.*, Nucl. Phys. B407 (1993) 515.
8. C. Quigg, M. H. Reno and T. Walker, Phys. Rev. Lett. 57 (1986) 774; M. H. Reno and C. Quigg, Phys. Rev. D37 (1988) 657.
9. R. Gandhi, C. Quigg, M.H. Reno and I. Sarcevic, hep-ph/9512364, submitted to Astropart. Phys.
10. A. Dziewonski, "Earth Structure, Global," in The Encyclopedia of Solid Earth Geophysics, ed. D. E. James (Van Nostrand Reinhold, New York, 1989), p. 331.
11. P. Lipari and T. Stanev, Phys. Rev. D44 (1991) 3543.
12. E. Eichten, I. Hinchliffe, K. Lane and C. Quigg, Rev. Mod. Phys. 56 (1984) 579.
13. H. Lai *et al.*, Phys. Rev. D51 (1995) 4763.
14. W. H. Rhode *et al.* (Fréjus Collaboration), Wuppertal preprint WUB-95-26, to appear in Astropart. Phys.